Meteor Showers in Review

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Abstract

Recent work on meteor showers is reviewed. New data is presented on the long duration showers that wander in sun-centered ecliptic coordinates. Since the early days of meteor photography, much progress has been made in mapping visual meteor showers, using low-light video cameras instead. Now, some 820,000 meteoroid orbits have been measured by four orbit surveys during 2007–2015. Mapped in sun-centered ecliptic coordinates in 5° intervals of solar longitude, the data show a number of long duration (> 15 days) meteor showers that have drifting radiants and speeds with solar longitude. 18 showers emerge from the antihelion source and follow a drift pattern towards high ecliptic latitudes. 27 Halley-type showers in the apex source move mostly towards lower ecliptic longitudes, but those at high ecliptic latitudes move backwards. Also, 5 low-speed showers appear between the toroidal ring and the apex source, moving towards the antihelion source. Most other showers do not last long, or do not move much in sun-centered ecliptic coordinates. The surveys also detected episodic showers, which mostly document the early stages of meteoroid stream formation. New data on the sporadic background have shed light on the dynamical evolution of the zodiacal cloud.

Keywords: meteors, meteor showers, meteoroids, celestial mechanics, minor planets
1. Introduction

A working list of meteor showers is maintained at the International Astronomical Union's Meteor Data Center (Jopek & Kanuchova, 2016). At the time of writing, 701 proposed showers are catalogued, of which 112 meteor showers are certain to exist. Of those, only 32 have known parent bodies. Efforts are underway to identify more (e.g., Kholshevnikov et al., 2016; Micheli et al., 2016).

It is important to better document these showers, and search for more, because meteor showers provide a unique record of past comet activity. They document the meteoroid stream dynamics that will result ultimately in replenishing the zodiacal dust cloud. For reviews, see Jenniskens (2006, 2015a, 2016a) and Williams & Jopek (2014).

Fundamental questions remain. Comet disruptions are the main mass-loss mechanism of comets contributing to meteoroid streams and the zodiacal cloud (Jenniskens, 2008a,b; Nesvorny et al., 2010, 2011; Yang & Ishiguro, 2015; Ye et al., 2015b), but what are the velocity dispersions that result from that? On what timescale do comets disrupt? When did individual streams form? What are the long-term dynamical and physical processes that form the zodiacal cloud? Even the collisional lifetime of meteoroids is uncertain (Jenniskens et al., 2016c).

To find answers to these questions, meteoroid streams at Earth need to be charted and modeled to explain all observed shower features. With each triangulated meteor that provides entry speed and approach direction (the radiant), a new dot is placed on a map that gradually brings out the meteor showers. The showers are best recognized after removing the Earth's motion, by subtracting the solar longitude from the ecliptic longitude of the radiant to calculate sun-centered ecliptic coordinates (Fig. 1).

It is also important to map these showers at different particle sizes. There are striking differences between maps derived from radar and optical observations, which provide clues to the forces and disintegration mechanisms at work. Water vapor drag during ejection and the Poynting-Robertson drag, for example, are particle size dependent.

Since the last Meteoroids meeting in Poznan in 2013, a large number of newly detected meteor showers have been reported. Several exceptional meteor showers have occurred. Progress has been made in understanding meteoroid stream evolution and the dynamics of the sporadic background. A few more parent bodies have been identified. Many questions remain. This review will highlight some of the advances, present some new results regarding long-lasting showers, and reflect on outstanding problems.

2. Methods: the meteor shower sky at different meteoroid sizes

At peak visual magnitudes brighter than -12, roughly corresponding to masses above ~10 kg and diameters above 20 cm, meteors are mostly due to the impact of asteroidal matter (Borovicka et al., 2015). Less than 100 of such fireball trajectories have been published. In addition, satellite-derived data has been released that pertain to meter-class impacts (Brown et al., 2016). Based on some orbit pairings, newly discovered meteoroid streams have been proposed and linked to near-Earth asteroids, given that rubble pile asteroids may loose debris. However, so far those associations have not been proven statistically significant (e.g., Koten et al. 2014; Jopek & Bronikowska, 2016).
Between -12 and -5 magnitude, the sample is larger. Figure 1 shows the radiant distribution, corresponding to meteoroids about >3 cm in size, 20 g in mass with median speed of ~23 km/s. About 800 trajectories have been published, many of which are gathered in the IAU photographic meteoroid orbit database. In the near future, numbers are expected to increase significantly as a result of the expanded all-sky video and digital still-camera network expansions (e.g., the European Network, the Desert Fireball Network, the NASA All Sky Fireball Network). Some 35–70% of meteors belong to showers (e.g., Fig. 26.7 in Jenniskens, 2006). With the exception of Halley-type annual showers, few sporadic meteors of this brightness come from the apex source. The data so far show that most meteors in this brightness range originate from the antihelion source, including a significant contribution from the Taurids and Geminids (Fig. 1). It remains to be determined how much of this is an instrumental effect: many past photographic campaigns targeted meteorite falls and annual meteor showers.

Four large surveys are under way to map the meteors in the +4 to -4 magnitude range, about 1-cm sized meteoroids of mass 1g. Figure 2 shows their annual yield. The 100-camera SonotaCo network in Japan is based on Touru Kanamori’s "UFO Capture" software for meteor detection. The 200-camera Cameras for Allsky Meteor Surveillance network in California, the Netherlands and New Zealand, as well as the Croatian Meteor Network, is based on Peter Gural's "MeteorScan" software for meteor detection. The Edmond database is rooted in both UFO Capture and Sirko Molau's "MetRec" software. All are supported by amateur meteor astronomers. At the end of 2015, our CAMS network had measured 340,000 orbits and all video-based networks together about 820,000. Results for 320 showers and shower-components are presented in Jenniskens et al. (2016a, 2016b, 2016c) and Jenniskens and Nénon (2016). 36% of all meteors in CAMS data originated from meteor showers (Jenniskens et al., 2016c).

Figure 3 shows a single five-degree wide interval in solar longitude centered on 140º, color-coded according to geocentric entry speed. The sporadic sources are well detected, as are many showers. Since the 2013 Meteoroids meeting, the CMN added showers #509–622 (Korlevic et al., 2013; Andreic et al., 2014; Gural et al., 2014; Segon et al., 2014), while CAMS added showers #623–750 to the IAU Working List (Rudawska & Jenniskens, 2014; Jenniskens et al., 2016a–c). The bottom figure shows the combined data, illustrating the bulls-eye pattern of entry speed caused by Earth's motion around the Sun directed to ecliptic longitude 270º and ecliptic latitude 0º. Within each band there is a range of entry speed.

Showers are also recognized in specularly reflected radar returns just fainter than the ~+5 magnitude underdense echo limit (both daytime and night time showers). The Canadian Meteor Orbit Radar has detected mostly +8 to +6 magnitude meteors (~0.1 cm size, ~1 mg mass at 19 km/s), but is most sensitive in the 20–50 km/s range of entry speed (Brown et al., 2010). A recent example of CMOR data is shown in Brown (2016), who reports that CMOR routinely identifies ~150 annual meteor showers. The southern hemisphere SAAMER meteor orbit radar covers about +10 to +6 magnitude (Michell et al., 2015). The antihelion source apex and toroidal sources have similar strength. About 10% of meteors are assigned to showers (Brown et al., 2010). Especially some of the toroidal showers, such as the Psi Cassiopeids (PCA) in July, are very strong in CMOR data and hardly or not at all detected by CAMS. Since the Meteoroids 2013 meeting,
SAAMER added showers ##756–792 (Janches et al., 2013) and CMOR added ##793–795 (Brown, 2016) to the IAU Working List of Meteor Showers.

Meteors fainter than +10 magnitude are even more dominated by sporadics. Only about 1% of meteors are in showers in the former narrow-beam specular AMOR radar survey in New Zealand, which was able to detect about +14 magnitude meteors (~0.01 cm, ~ 1 µg mass) (Galligan & Baggaley 2005). Large aperture radars, the single-dish Arecibo radar in Puerto Rico, and the ALTAIR radar in Kwajalein and the interferometer Synthetic Aperture Radars (notably the Mu-Radar in Japan, the Jicamarca radio observatory in Peru, MAARSY in Norway, and EISCAT in Sweden) can detect meteor head echoes at these small sizes, tracking the meteors themselves. At these small sizes, the sky is dominated by the apex source of fast 50–72 km/s meteors (Janches et al., 2015a, b). The eta-Aquarids are most readily detected (Kero et al., 2012), but other showers were studied also (Kero et al., 2013; Fujiwara et al., 2015).

3. Results: the newly identified wandering showers

Fig. 1 illustrates the sad state of affairs ten years ago, when many proposed meteor showers were based only on alignments of a handful of meteoroid orbits (e.g., Jenniskens, 2006; Campbell-Brown & Jones, 2006). That has changed dramatically as a result of the new video-based and radar-based orbit surveys.

When I plotted up the 820,000 video-generated orbits from the main video surveys in sun-centered ecliptic coordinates, in 5° intervals of solar longitude (e.g., Fig. 3), the resulting movie showed a surprising amount of motion. It turns out there are many wandering showers that last longer than 15 days and drift in entry speed and sun-centered ecliptic radiant coordinates (Tab. 1–3).

3.1. Those that emerge from the Antihelion source

Most striking are the wandering showers that are in, and emerging from, the antihelion source. Table 1 gives a complete list of all such detected showers. The list contains some familiar names, such as the kappa Cygnids and Taurids, but several showers come as a surprise to me. Some are not even established, but all deserve to be so.

Their motion is depicted in Fig. 4, all moving initially from high to low ecliptic longitudes, but some reversing course at high ecliptic latitudes. It is surprising to see the showers turning on rapidly, then persist for many weeks and turning off rapidly. Some aligned showers may be from the same source. The May psi Scorpiids (MPS) precede the kappa Cygnids (KCY) and show a smooth change in entry speed after a small gap in activity (Fig. 5). When the ecliptic latitude increases, the velocity change reverses sign. The same velocity behavior is seen with the omicron Eridanids (OER), but there is no gap in activity. Because there is no gap, the second component was not given its own name.

A few other interesting things deserve notice. When plotting the meteor entry speed versus solar longitude for a 5° wide band centered on the two Taurid branches, both the northern and southern branch have a sharply defined component with a steep gradient of speed versus solar longitude (Fig. 6). In the southern branch, this component is known as the Southern chi Orionids (ORS). At high solar longitudes, it has a distinct radiant position from the Southern Taurids (Jenniskens et al., 2016a). Based on Fig. 6, I conclude
that there is also a Northern chi Orionids (ORN), as marked, which is a big part of the activity of the northern branch. From this new interpretation of the data, the Northern Taurids (NTA) are the diffuse activity that creates a wedge just below the ORN band. The velocity dependence of the ORN is not as steep as for the ORS but they cover the same range in solar longitude. These meteoroids could have evolved to rotate the nodal line sufficiently to be seen at both branches. Much of the Southern Taurid showers are not reflected in the northern branch, and vice versa.

Jenniskens et al. (2016a) noticed that the Taurids and chi Orionids appear to consist of a series of showers covering a narrow interval in solar longitude. This pattern is still visible in Fig. 6, where Taurids clump in short ranges of solar longitude. Only around 210° and 260°, is there a noticeable difference in the sporadic background that can be attributed to differences in effective coverage. Several of these components were assigned to different parent body candidates, all with semi-major axis about 2.2 AU (Jenniskens et al., 2016a). This paints a picture of a disintegrating comet leaving 2P/Encke and a series of comet fragments and meteoroids behind. Fragments and meteoroids contained about as much mass as 2P/Encke. More recently, these comet fragments continued to disintegrate and those disintegrations are responsible for the components, and most of the Taurids we see at Earth now (Jenniskens et al., 2016a).

This pattern of comet disintegration can also be seen in the alpha Capricornid shower. That shower's main component is associated with comet 169P/NEAT (Jenniskens & Vaubaillon, 2010; Kasuga et al., 2010). At shorter solar longitudes, CAMS also detected a second component, the ξ²-Capricornids (XCS), which matches to the orbit of SOHO comet C/2003 T12 (Jenniskens et al., 2016a). At longer solar longitudes, activity continues and this component is now seen to wander quite far from the antihelion source (Fig. 4, labeled "CAP").

Similarly, the showers of the Machholz complex show interesting patterns of radiant and velocity drift that suggest they are composed of different components from different periods of disintegration (Jenniskens et al., 2016a). The main component of the delta Aquariids, for example, is off-set from the drift depicted in Tab. 1. It remains a puzzle why the radar-detected Daytime Arietids are in such short orbits compared to those detected by optical techniques (Bruzzone et al., 2015).

To create such wandering showers, the disintegration does not need to have happened long ago. Comet 3D/Biela broke only in 1842 or 1843, but generated a meteoroid stream, the Andromedids, that are now detected as one of the wandering showers (Tab. 1).

Several authors have shown that such wandering showers from Jupiter Family comets can be created by precession in a few thousand years, from a rotation of the nodal line (e.g., Babdzhanov 2003, Sekanina & Chodas, 2005; Jenniskens, 2006; Babdzhanov et al., 2008; Trigo-Rodriguez et al., 2009; Wiegert et al., 2013). Most recently, Moorhead et al. (2016) investigated potential kappa Cygnid parent bodies and found that the precession rate varies between ~2,000 and 9,000 years for meteoroids on slightly different orbits. In detail, their Fig. 6 shows rapid changes, presumably during periods of close encounters with Jupiter, followed by a more gradual precession of the nodal line. Sekanina & Chodas (2005) invoked this effect of close encounters with Jupiter to suggest a rapid evolution of the Machholz complex, some components of which are very young (Jenniskens, 2006; Abedin et al., 2015).
3.2. Wandering showers in the apex source

The apex source has many showers that are active for several days without changing sun-centered ecliptic coordinates (Kornos et al., 2015; Jenniskens et al., 2016a, 2016b, 2016c). In addition, there are at least 27 that do (Tab. 2). Most move from high to low ecliptic longitude (left to right in the diagram of Fig. 4), but some highly inclined showers, including the Perseids, move the opposite way.

Many are readily identified as originating from known Halley-type comets: the Perseids from 109P/Swift-Tuttle, the Leonids from 55P/Tempel-Tuttle, and the Orionids from 1P/Halley, for example. Indeed, it is likely that all showers in Tab. 2 are from Halley-type comets.

Of these, the eta Aquariids were recently studied from CMOR radar observations, and found active between solar longitudes 35–60º (Campbell-Brown & Brown, 2015). Optical observations detect the shower between 25–80º (Table 2). The activity profile shows no mass dependence between microgram and milligram sizes (Jenniskens 2006, Campbell Brown & Brown, 2015), so most dispersion is due to gravity and not from one of the size-dependent processes.

Various meteoroid stream formation models show that Halley-type comets can precess significantly over time and create meteoroid streams that are dispersed over a wide range of node (McIntosh & Jones, 1988). Harris et al. (1995) invoked ejection velocity and non-gravitational forces to create a range of orbital periods, causing different precession rates for meteoroids in orbits of different orbital period. Gravitational perturbations, however, may be more important in dispersing the orbital periods (Jenniskens, 2006).

3.3. Toroidal source showers

The toroidal source is mainly due to the Kozai resonance, a large-amplitude cycling of inclination and perihelion distance that results in meteoroids meeting Earth's orbit preferentially at their highest inclination (Wiegert et al., 2009). Most showers in the toroidal source appear and disappear with none or only small changes in sun-centered ecliptic coordinates of the radiant.

The showers detected tend to be rich in small particles and many are prominent in CMOR data (Brown et al., 2010). They also tend to show short semi-major axis orbits in the radar data. Many prominent CMOR showers are not detected by optical techniques. Pokorny et al. (2014) determined that the long-term stable part of the toroidal particles is mainly fed by dust released from Halley type comets.

3.4. Slow meteors in between the toroidal and apex sources

I noticed another interesting feature in these maps: there are very dispersed groups of slow meteors in between the toroidal ring and the apex source. They move in time towards the antihelion source. In some cases, they converge with a known low-perihelion distance shower on the inner edge of the antihelion source.

A clear example is the theta Aurigids, a shower that is leading up to the Geminids (Jenniskens et al., 2016a). Other examples are listed in Table 3. In general, the low entry
speed of these meteors translates to a short (asteroidal-like) semi-major axis orbit. To understand what is causing these showers, this phenomenon deserves to be modeled.

4. Results: Meteor shower outbursts

The meteoroid orbit surveys also detect meteor outbursts. In contrast to the evolved streams, these are meteor showers, or shower components, from streams so little evolved (and spatially or temporally confined) that they do not return annually. They often represent dust released only one or a few orbits back in time, or are due to older dust trapped in mean-motion resonances. Some meteor outbursts can be predicted. Many such predictions are listed in Jenniskens (2006). Recent predictions were made for 1-revolution dust trail encounters from long period comet C/2015 D4 (Borisov) (Jenniskens et al., 2015a), and comets 12P/Pons-Brooks (Tomko & Neslusan, 2016) and 15P/Finlay (Ye et al., 2015a).

Table 4 lists the meteor outbursts that have occurred since 2013. Those that were predicted are marked "*". Many are not. It is an ongoing effort to document the irregular shower activity from year to year.

The unexpected October 8, 2012, Draconid meteor outburst appears to have been caused by dust particles released during the 1966 perihelion passage of the parent comet 21P/Giacobini-Zinner (Ye et al., 2014). Future Draconid outbursts are predicted for 2018, 2019, 2021, and 2025.

The May 24, 2014, encounter with comet 209P/Linear was predicted (Jenniskens, 2006) and produced a meteor shower called the Camelopardalids, rich in faint meteors (Jenniskens et al., 2014a,b; Younger et al., 2015). Low escape velocities suggested these meteoroids just barely escaped from the comet nucleus (Ishiguro et al., 2015). The lack of bright meteors was attributed to meteoroids falling apart in the interplanetary medium (Jenniskens, 2014b, 2015c; Ye et al., 2016a).

Predictions made ahead of the close March 2016 approach of mostly dormant comet 252P/Linear and its fragment P/2016 BA14 (PANSTARRS) showed that dust trails were just outside of Earth's orbit (Ye et al., 2016b). Only stray meteoroids could intersect with Earth. No activity has been reported.

More often, meteor outbursts occur unexpectedly. Nice outbursts of the kappa Cygnid in 1993 (Jenniskens, 2006), 2007 (Koseki, 2014), and again in 2014 suggest that meteoroids are trapped in the 5:3 interior mean motion resonance with Jupiter (7.116 years), dispersing only gradually along the comet orbit (Moorhead et al., 2016). However, Rendtel & Arlt (2016) did not find such periodic pattern in visual shower activity. Also, the measured meteoroid orbits do not cluster at the 5:3 resonance itself. Moorhead et al. found that the semi-major axis of CMOR meteoroids clusters around several resonances, the 3:1, 9:4 and 5:3 mean-motion resonance, but the more precise EN fireballs are mostly found just in and outside the 5:3 mean-motion resonance. Sekhar et al. (2016) proposed that in some cases, for example during past Perseid outbursts, three-body resonances may be at play.

Unexpected outbursts include those of the April alpha Capricorinids (Kanamori et al., 2015), the kappa Cancrids and gamma Lyrids (Brown, 2016), and the spectacular chi Cygnids. The last shower was active over nearly the entire month of September in 2015, but was not known before. It was detected from CAMS data by the CAMS BeNeLux
network (Jenniskens, 2015b).

Perhaps the most delightful surprise in recent years was a southern hemisphere shower that was active on New Year’s eve in 2015, at the same time when fireworks were being launched, and on the first two days of the new year (Jenniskens et al., 2016b; Younger et al., 2016). Now known as the Volantids, this is the first shower listed in the IAU Working List from a small southern hemisphere constellation named after flying fish.

5. Discussion of meteoroid stream dynamics

Answers to some of the fundamental questions that were posed in the beginning of this review were obtained from a systematic analysis of CMOR and CAMS data. By searching for meteoroid streams in the orbit of known dormant comets, Ye et al. (2016) determined that 2.0 +/- 1.7% of the near Earth Object population is composed of dormant comets that in recent years created a detectable meteoroid stream. This suggests that the dormancy rate among active comets is at least 10^5 per year. The low dormancy rate confirms that disruption and dynamical removal are the dominant end states for near Earth Jupiter Family comets (Ye et al., 2016).

So far, no meteoroid stream has been linked directly to the aftermath of a recent disintegration of (part of) a comet nucleus. The 1872 and 1885 Andromedid storms, for example, appear to have been caused by normal ejection during the 1846 and 1852 returns of comet 3D/Biela (Jenniskens & Vaubaillon, 2007). If Earth is to encounter recently released debris from a comet disintegration, meteor showers more intense than what were seen in the past 200 years may be in our future.

Meteoroid streams may not last very long. The dynamical lifetime of a meteoroid, after which planetary perturbations eject it from the solar system or send it into the Sun or planets, can be calculated. More uncertain are the rates of destruction from collisions with other meteoroids and from disintegrations caused by temperature changes, electric charging, spin-up, etc. With the advance of meteoroid stream formation modeling and meteor shower observations, there is mounting evidence that meteoroids disintegrate before dispersing widely. Meteor outbursts are not always as intense as predicted, more so if the trails are many revolutions old. The timescale of meteoroid disintegration appears to have been particularly short for the fragile Camelopardalids, estimated by Jenniskens (2014b) to fade on a timescale of 30–50 y. Leonid dust trail density seems to decrease on a timescale of ~150 y to understand the disappointing rates for dust trails of more than 6 orbital revolutions, while the Taurids fade on a timescale of ~4,000 y to account for the lack of symmetry in Northern and Southern Taurid components (Jenniskens et al., 2016c). Ye et al. (2016) pointed out that if meteoroids last longer, then there should have been many streams whose parent bodies have already been disrupted or dynamically removed.

The rapid disintegration of large meteoroids may also explain some features observed in the sporadic meteor background. CAMS sporadic meteors still mostly have the semi-major axis of their source comets, a ~ 2.2 AU, while the smaller meteoroids detected by CMOR and AMOR peak at a shorter a ~ 1.0 AU (Jenniskens et al., 2016c). Poynting-Robertson drag is thought to be responsible for the shortening of the orbits. Interestingly, CAMS still detected a small population of short a ~ 1 AU orbits in the antihelion source,
suggesting that some larger grains survive in the interplanetary medium against collisions for several million years (Jenniskens et al., 2016c). This is ten times longer than proposed by Grün et al. (1985) and Soja et al. (2016). Earlier, Nesvorny et al. (2011) compared the orbital element distributions measured by AMOR (~0.1 mm grains) and CMOR (~1 mm grains) and concluded that the larger CMOR grains survived collisions 3 times longer than expected, both grain sizes having about the same lifetime.

In my opinion, this points to an evolutionary picture in which large meteoroids disappear by some form of thermal or electrical disruption, rather than collisions, before the meteoroid streams have dispersed widely. The smaller grain fragments populate the zodiacal cloud and survive for ~300,000 years. Also contrary to the model of Grün et al. (1985), at the small end of the size spectrum, grains < 100 micron are likely lost by collisions before Poynting-Robertson drag can circularize the orbits (Jenniskens et al., 2016c).

6. Showers on other planets

The close encounter of comet C/2013 A1 (Siding Spring) to Mars on October 19, 2014 (Vaubaillon et al., 2014; Ye et al., 2014; Ye and Hui, 2014; Moorhead et al., 2014) resulted in the detection of a metal atom layer high in the Martian atmosphere causing strong airglow in the metal ion line of Mg+ (Schneider et al., 2015). The airglow emission was detected in part because such glow is absent in the upper atmosphere of Mars in normal years. Sadly, efforts to image meteor showers directly from space or by the Mars rovers were not possible due to shut-down during the shower and lack of power at night and local dust storms (Jenniskens, 2014). Moreover, instruments so far taken to Mars were not designed for meteor observations (Domokos et al., 2007).

Closer to home, meteor showers were found to play a significant role in the occurrence of lunar impact flashes (Suggs et al., 2014; Robinson et al., 2015) and LADEE's periodically dusty lunar atmosphere (Stubbs et al., 2015; Colaprete et al., 2016).

Finally, Christou et al. (2015) proposed that seasonal variations of the calcium emission from Mercury's exosphere are related to surface impacts from the meteoroid stream of comet 2P/Encke.

7. Conclusions and future work

Much work is ahead to explain the observed features of meteoroid streams. The status of meteoroid stream modeling is still in its infancy. Many models fail to explain even the most basic features of the observed meteor showers. Dynamical models of the zodiacal cloud also still need to address fundamental issues, such as the short semi-major axis of radar-detected apex-source meteors and the nature of the toroidal complex.

The future for data collection and monitoring of meteor showers is looking bright. Satellite observations of bright fireballs continue to be made and some of that data is now public. The fireball networks are expanding and are expected to generate large numbers of meteoroid orbits soon. The existence of meteoroid streams from meteoroid impacts on rubble-pile asteroids may be proven. The video-based optical networks continue to expand with better and cheaper cameras coming out. This enabled the recent expansion of
the CAMS network to Arizona and the United Arab Emirates. More meteor outbursts will be recorded. CMOR is continuing to operate, now in the company of SAAMER and other southern hemisphere meteor wind radars. Large aperture radar observations continue to be made and are expected to give more insight into the dynamical evolution of the smallest particles in the zodiacal cloud.

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Figure 1: Radiants of photographed meteors brighter than -5 magnitude, from the 2003 IAU MDC photographic database. The main source regions are identified, as well as the Perseid (PER) and Geminid (GEM) showers.
Figure 2: Yearly tally of meteoroid orbits from the four largest video-based meteoroid orbit surveys.
Figure 3: Distribution of radiants, color coded by entry speed $V_g$ from slow (blue) to fast (red) in 5 km/s intervals. (a) Data for the five-degree wide interval in solar longitude centered on 140º. (b) Combined data for the whole year and all years.
Figure 4: Radiant drift for showers that show significant motion in sun-centered ecliptic coordinates. Crosses are markers in intervals of $5^\circ$ solar longitude.
Figure 5: Entry speed versus solar longitude for the longitude range that covers the showers May psi Scorpiids (MPS) and kappa Cygnids (KCY). Also marked are the July gamma Draconids (GDR).
Figure 6: As Fig. 5, for meteors in a 5° wide band in ecliptic radiant coordinates centered on the Northern Taurids (NTA) and Southern Taurids (STA). The Southern chi Orionids (ORS) and Northern chi Orionids (ORN) are marked as located between the two bars in each graph.
Table 1: Long duration showers with changing sun-centered ecliptic radiant that emerge from the anti-helion source. Solar longitude and geocentric coordinates of the radiant for the first and last 5º interval in which the shower was detected.

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<th>Shower</th>
<th>Code</th>
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<th>R.A., Dec. (º)</th>
<th>$V_g$ (km/s)</th>
<th>$\lambda_0$ last (º)</th>
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<td>&quot;</td>
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<td>265</td>
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<td>22.4</td>
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*) Not yet established
### Table 2: Long duration showers with changing sun-centered ecliptic radiant in the apex source. Solar longitude and geocentric coordinates of the radiant for the first and last 5° interval in which the shower was detected.

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<th>Code</th>
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<th>R.A., Dec. (°)</th>
<th>Vg (km/s)</th>
<th>( \lambda ) last (°)</th>
<th>R.A., Dec. (°)</th>
<th>Vg (km/s)</th>
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<td>99.7, +13.9</td>
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<td>59.4</td>
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<td>150.0, -8.4</td>
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*) Not yet established
Table 3: Long duration showers with changing sun-centered ecliptic radiant and short semi-major axis. Solar longitude and geocentric coordinates of the radiant for the first and last 5º interval in which the shower was detected.

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<th>R.A., Dec. (º)</th>
<th>$V_g$ (km/s)</th>
<th>$\lambda_0$ last (º)</th>
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<td>106.1, +32.6</td>
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<td>311.0, -2.3</td>
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*) Not yet established; † Early Geminids (GEM); § Also possibly gamma Taurids (GTA) towards end of interval.
Table 4: Meteor outbursts in the period 2013–2016.

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<th>Vg (km/s)</th>
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<td>2013-09-09</td>
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<td>2015-09-01–28</td>
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